Technical Note N-1130

IMPROVED TECHNIQUES FOR THE NON-DESTRUCTIVE TESTING OF DIESEL ENGINE PISTONS

By

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ABSTRACT

Repeated and catastrophic piston failures in a group of large diesel engines deployed in Vietnam for power generation purposes. revealed the urgent need for the development of a fast, reliable means for the detection of incipient failures in these engines.

As a result of work subsequently performed by the ROICC-Pacific and various agencies and consultants under his direction, a very successful non-destructive testing technique was established. This technique utilized commercial ultrasonic instrumentation of the pulse-echo type. The procedure, as finalized, will unfailingly detect cracks in the major webs of the diesel engine pistons under consideration, and requires only the removal of the cylinder head for access to the piston top.

The only major constraints in the application of this technique are the requirements that: (1) the piston material be homogeneous, (2) detailed information relating to piston configuration be available, and (3) the diagnosis be made by technical personnel experienced in ultrasonic interpretation.

INTRODUCTION

In 1967 the U. S. Navy purchased twenty-seven diesel-engine-driven generator sets, each rated at 1,200 kw, for use in power generating stations throughout Vietnam. Almost immediately following the installation of these engines, they were plagued by a repetitive series of major mechanical failures which resulted from cracked pistons, and the subsequent separation of piston head and body.

A comprehensive investigation into the cause of this trouble, and the development of techniques for the correction of the difficulties was assigned to the Resident Officer in Charge of Construction, Naval Facilities Engineering Command Contracts, Pacific, San Bruno, California. This organization, in turn, contracted with a number of specialized government and private consultants for assistance in specific areas of the investigation. These specialists included:

1. Thermo Research Associates, Inc.
   Consulting Engineers
   Palo Alto, California

2. Anamet Laboratories, Inc.
   Metallurgical Investigators
   Berkeley, California

3. San Francisco Bay Naval Shipyard
   Quality & Reliability Assurance Department
   Vallejo, California

4. Naval Civil Engineering Laboratory
   Mechanical & Electrical Engineering Department
   Port Hueneme, California

Initial investigations of the problem led to the conclusion that the piston failures were due to a combination of factors, including such items as:

1. piston design

2. mat· .ial selection

3. quality control during casting

4. heat treating procedures

An additional factor which was suspected, but which could not be definitely pinpointed, was that of operational and maintenance conditions at the site of operations in Vietnam.

Further studies developed the urgent need for a rapid, reliable method for detecting incipient failure in these diesel engine pistons, and also pointed out the fact that an acceptable method of detection must be usable without the necessity of completely disassembling the engine and removing the pistons from their cylinder bores.

A detailed examination of available non-destructive testing techniques eliminated all but "ultrasonics" as unsuitable for this application. It was therefore decided to concetrate on the development of an Ultrasonic Inspection Procedure[1,2] which would accomplish the desired results.

PROCEDURES AND RESULTS

The first step in the development of the improved, non-destructive inspection technique was to conduct a thorough investigation and diagnosis of in-service piston failures. This involved an inspection and analysis of all defective pistons returned from Vietnam. See Figure 1 for an illustration of typical pistons as received. These pistons, manufacturer's part no. G-6924, are from Model DSG Enterprise diesel engines. The pistons are approximately 12 inches in diameter, by 20-3/8 inches high, and weigh between 185 and 188 pounds each. They are of one-piece construction, are machined from a ductile, nodular cast iron, and have a vertical-section configuration as indicated in Figure 2. Nodular cast iron is a relatively recent development in engineering materials. It is similar in some respects to gray (flake) iron, but is distinguished from it primarily because of the spheroidal shape of its graphite particles. The spheroidal graphite, in turn, results in improved mechanical properties in nodular cast iron, as compared to those of gray iron.

Initially two new, unused pistons were supplied for examination, and for use as a basis of comparison. Subsequent examination of all available defective and suspected pistons indicated that the cracking, and ultimate failure, originated along the inner major radius profile of any of the four major webs inside the piston, and propagated radially outward toward either of the two upper ring grooves (as illustrated in Figure 2). As the engine continues to operate, this cracking continues to develop circumferentially around the piston, until finally the top portion, or crown, separates from the piston body with disastrous results to the engine.

In order to provide additional background information and a standard for future verification, selected cracked or suspected pistons were thoroughly inspected via the magnetic particle method,[3] and all crack indications carefully charted. In addition, all pistons were subjected to:[4] (1) X-ray examination for detection of porosity and cracks, (2) chemical analysis of piston material, (3) tensile strength tests of piston material, and (4) microscopic examination of material grain structure.

The sought-for breakthrough in the development of the improved inspection technique came with the discovery of two pistons which had been in operation for approximately 2,000 hours, and which had, as a result of this operation, developed typical cracks (see Figure 3) that extended through each of two of the four major webs inside the piston, and along the piston outer wall for approximately 1/4-inch in each circumferential direction from the web. These pistons provide examples of major webs having both sound material and actual service-induced cracks at the "threshold-of-failure" stage.

As previously mentioned, it was concluded that ultrasonic inspection was the only successful detection of incipient piston failures, without the necessity of complete engine disassembly. Extensive experimentation with ultrasonic equipment on the two "suspected" sample pistons resulted in proof that this technique was capable of providing the required information, and that it was, in addition, as reliable, less expensive, and less time-consuming than equally thorough inspection by any other known method.

Basic Principles of Ultrasonic Inspection

Non-destructive testing, based on the propagation and detection of ultrasonic sound waves, is finding increasing use in government and industry for the discovery and measurement of flaws and discontinuities in solid materials.

Ultrasonic waves are considered to be those having frequencies greater than 20,000 cycles per second, which is above the hearing range of the normal human ear. Most commercial ultrasonic testing is now performed at frequencies between 1 and 25 megacycles per second, with 1.0 to 5.0 megacycles being the most used range. These waves travel through homogeneous materials, but are reflected at boundaries between dissimilar materials, and at discontinuities within any given material.

The velocity of ultrasonic waves, like that of audible sound waves, depends upon the properties of the medium of propagation. Most common materials transmit ultrasonic waves very well in the range of 1.0 to 10.0 megacycles per second. For good propagation, the material should be reasonably homogeneous, have a fine grain structure, and not be excessively anisotropic, that is, it should not exhibit different properties when tested along different axes or directions.

Whereas sound has a relatively constant velocity through aluminum and mild steel, both of which are homogeneous structures, the velocity at which ultrasonic sound waves are transmitted through cast iron (the material under consideration herein) is effected by various conditions in the iron, such as the size, shape, and distribution of graphite, and the microstructure. Cast iron is therefore considered, for this purpose, as a non-homogeneous material.

Graphite is, of course, one of the major constituents of cast iron, and its presence in either flake or nodular form constitutes

inhomogeneities in the structure. Graphite, as it occurs in one of three different forms -- flake, undercooled, and nodular -- offers a different resistance to sound travel in each. The speed of sound is lowest and uncertain in soft, large-flake, hypereutectic irons -- averaging only about 130,000 inches per second (under which conditions the ultrasonic detection of flaws is most difficult).

As the amount of undercooled graphite increases, sound velocity increases also, until an almost completely undercooled graphite structure exhibits a sound velocity of approximately 160,000 inches per second. Between a fully undercooled graphite structure and one that is 20 to 30% nodular, unobstructed sound transmission ability increases very rapidly to the area of 205,000 inches per second, wherein ultrasonic testing becomes most effective. As the percentage of nodularity increases still further, sound velocity continues slowly upward, until at 90% nodular, the velocity is within the vicinity of 215,000 inches per second (see Figure 4).

The search unit or probe from which the ultrasonic wave emanates consists of a nautural or man-made crystalline material possessing piezoelectric properties. Examples are Rochelle salt, quartz, lithium sulfate, and artificial ceramic materials, such as barium titanate and lead metaniobate. The exact frequency of the pulse is, in turn, controlled by the thickness of the transducer material. The application of an electrical field to the crystal causes its dimensions to vary with the frequency of the applied field. Conversely, if pressure is exerted on the face of ths crystal, it will generate a small voltage of the same frequency as the applied vibration, and thus enable the reception of vibrations from the item being inspected.

The crystal is actuated for a controlled period of time (2 millionths of a second, or less), resulting in a burst of sound waves. The crystal then ceases to vibrate for a period sufficiently long to receive the returning echoes. This cycle of transmitting and receiving is repeated at a rate varying from 60 to 1,000 times per second, depending upon the type of instrument being used.

Instrumentation for this pulse-echo technique (the most commonly used ultrasonic system) comprises a pulse oscillator, a modulator, a transducer, a receiver-amplifier, a rectifier, a linear-sweep generator, and an oscilloscope (see Figure 5). When in operation, the output from the pulse generator is applied across the transducer, and conducted, via the liquid couplant, into the test item. When the ultrasonic wave strikes an interface, part of the energy is reflected. Receiver circuits then amplify the results of the reflection on the transducer to an amplitude suitable for operating the oscilloscope.

An discontinuity or flaw, as well as the back side of the specimen, returns the essential echo. The time interval between the initial pulse and the return of the echoes is measured on the oscilloscope, and the flaw can then be recognized by its position and amplitude in the echo pattern. With the horizontal sweep calibrated in terms of distance, the location of flaws, as well as the material thickness, can be measured directly.

Non-destructive testing via this method has a number of major advantages, which include:

1. High sensitivity and fast response, permitting the rapid location of small defects.

2. Great penetrating power, which allows for the examination of thick materials.

3. Requirement for access to only one surface of the object to be tested, thus limiting need for disassembly.

Possible disadvantages, which must also be considered, include:

1. Difficult signal interpretation is the case of unfavorable speciman geometry.

2. Weak signal display due to undesirable internal material structure (such as large grain size) which restricts the passage of ultrasonic energy.

3. Requirement for a high level of operator skill and training in interpreting oscilloscope patterns.

When comparing ultrasonic flaw detection with radiography, another means of accomplishing the same result, areas of ultrasonic superiority may be noted as follows:

1. Instantaneous results are given from one surface only.

2. There are no radiation dangers.

3. Film processing delays are eliminated.

4. Required equipment is relatively small and portable, may be battery operated, and is relatively inexpensive.

5. The process is particularly sensitive to small cracks and laminar defects, which are difficult to detect by radiography.

Variations of search unit and scanning techniques which were initially explored in this study included: (1) angle beam scan (15° and up), (2) dual element search units, (3) contour-fit adaptors (lucite and silicone putty), (4) liquid delay columns, and (5) transducers of assorted size and frequency. After analysing the results of all variations, it was concluded that a procedure based upon a basic straight beam scan would be the most expedient approach, for reasons as follows:

1. It is relatively uncomplicated and easy to understand.

2. Elaborate and expensive reference calibration standards are not required. (The inspected piston, itself, provides an excellent reference for both depth measurement and signal amplitude calibration.)

3. Couplant supply, clean-up, and contamination problems are minimized by utilizing readily available engine oil as the sound-transfer medium, in lieu of the more conventional water, glycerine, or cellulose gum solutions.

4. Complications due to special custom adaptors or wedges for the search units are eliminated.

5. Acceptance or rejection is very decisive, with little possibility of a "perhaps" category.

Test Equipment Requirements for Diesel Piston Inspection

Ultrasonic Pulse Generator. Specific instrumentation suitable for this application includes (but is not necessarily limited to) makes and models as follows:

1. Type UCD Reflectoscope
   Automation Industries, Inc.
   Danbury, Connecticut

2. Model PS-701 Pulse Ultrasound Instrument
   Magnaflux Corporation
   Chicago, Illinois

3. Model 301 Sonoray Ultrasonic Tester
   Branson Instruments, Inc.
   Stamford, Connecticut

These instruments are of the pulse-echo type having an "A-Scan" presentation. By way of explanation, when an echo signal is picked up by the same transducer that produce the original sound wave and this signal is in turn displayed on an oscilloscope, the system is designated as "A-Scan." "B-Scan" is a vector scan technique similar to radar that examines a cross-sectional echo pattern in two dimensions, while "C-Scan" produces a 2-D plot by using a raster-scan approach of the whole object by the shuttling of an ultrasonic transducer.

The majority of the commercially available units are portable instruments of small suitcase size, none weighing more than a total of 20 pounds. They are likewise completely self-contained and may be operated from a built-in battery, or, where available, may be plugged into a standard 115 volt, 60 cycle A.C. electrical system. Total cost does not exceed $3,000.00 each.

Search Unit, Complete with Connecting Cables, and Suitable Couplant. Ceramic element transducers, having a rated frequency of 5.0 MHz or less should be used. The selection of exact frequency for best results is always a compromise. The use of 5.0 MHz (the higher frequency) improves the resolution of the signal on the viewing screen. On the other hand, a lower frequency will provide better penetration of the material.

The overall size of the transducer contact area should be as small as practicable, as the ability of the transducer to fit the contour of the piston top is an important factor. "Fingertip" style transducers having a 1/4-inch or less nominal diameter will meet this requirement. If necessary the lower part of the housing may be modified to fit. The specific search unit successfully used in these tests was an Automation Industries, Model SFz, 5.0 MHz, 1/4-inch diameter unit. Any equivalent should be satisfactory.

The couplant, or medium for transmitting the sound waves from the transducer to the piston head, should be clean diesel engine lubricating oil of SAE 30 weight, or heavier. This substance is a satisfactory sound-transfer medium, is non-corrosive, is non-contaminating, and is readily available at the job site.

Calibration Procedure

A piston of the type under test is used as a calibration standard, both for sensitivity and depth.

The outer section of the piston top, located between the valve rim recess and the uppermost ring groove (see point "M" on Figures 6 and 7), provides a material reference calibration dimension of 1-1/4 inches.

The ultrasonic test instrument is now switched on, and allowed to warm-up. When the screen output has stabilized, the base-line trace is adjusted to the zero level, if required. With the aid of a china marking pencil, the base line of the scope is next divided into five evenly spaced subdivisions, and labeled 0 inch through 5 inches.

A transducer of the proper type is finally connected to the instrument and "coupled" to the piston at the outer edge of the valve rim recess area of the piston top rim, where the thickness to the first ring groove is 1-1/4 inches. (Point "M" on Figure 7). The instrument controls are adjusted so as to display four multiple reflections from the uppermost ring groove. By refining the sweep delay and sweep range control settings, the leading edge of the first, second, third, and fourth multiple reflections are now aligned with the 1-1/4 inch, 2-1/2 inch, 3-3/4 inch, and 5 inch markings, respectively, on the scope base line, thus completing the horizontal calibration (see Figure 8). Should it be impossible to satisfactorily distinguish the four multiple reflections on the scope (as illustrated in Figure 9), it may be assumed that the piston material is flake type cast iron, and is therefore not suitable for the inspection via this process.

For sensitivity (vertical) calibration, the search unit is "coupled" to the piston head in position "A" as illustrated in Figures 6 and 7. After obtaining an indication from the far edge of the major web (the major web at this point is identified as a double image at approximately 1-7/8 inches in depth), this signal is maximized by carefully scanning the transducer in each direction across the web. The instrument gain control is then adjusted so that the peaked indication is set at 80% of full screen height. During this maximizing process, any indication occurring on the screen at 7/8 inch depth, represents the interior wall of the piston head, and is evidence that the transducer is not correctly positioned over the deep center line of the major web.

With the web thickness signal occurring at 1-7/8 inches depth, and with the scope trace adjusted to 80% of full screen height, the equipment is now ready for scanning the complete piston web. It should be noted that a recalibration of signal-amplitude may be necessary for scanning the other three major webs of any particular piston, and that the inspection of other piston crowns will require a recalibration of the depth-measurement calibration, as well as of the signal-amplitude calibration.

Search Procedure

Following a successful calibration, continue the scan by carefully advancing the transducer out from the signal-amplitude calibration point "A" in a radial direction toward the rim recess. (Again see Figures 6 and 7 for scan path details). In this process it is essential that (1) the transducer position be maintained directly over the center line of the major web in question, and (2) there be no loss of proper "coupling" between the transducer and the piston crown.

As the scan progresses, the 1-7/8 inch depth signal will gradually diminish to zero level. This results from the sound waves being directed at the internal radius of the major web and reflected away from, rather than back to, the transducer. (Note position "1" of Figure 7.) This area of the piston has been found to be a very vulnerable point with regard to crack susceptibility. It is therefore essential that the inspector be especially alert in this area for any signal indication in the 1 to 2 inch depth range, which may be indicative of an incipient failure in the piston structure. (See Figure 10 for typical oscilloscope response to a cracked web.)

In continuing the scan outward from this point, if the web is sound, an indication will soon appear on the viewing screen at an approximate depth of 4-3/8 inches. (See position "2" in Figure 7 and Figure 11.) This is a reflection from the inner flange of the piston, and is evidence of satisfactory sound wave penetration through the major web profile. It should be noted that a continuation of the scanning from here on into the concave portion of the piston top surface will require a liberal "puddling" of couplant in order to adequately conduct the sound waves into the piston.

Considerable care must be exercised while searching for cracks in this area, as the web is thin and the search unit can be very easily moved off to one side or the other so as to miss it. If an indication should appear at 7/8-inch below the piston top surface, it shows that the search unit is not over the major web area, but has been moved out over the thin section of the piston head, which is a nominal 7/8-inch thick. It is recommended that the operator initially practice on a sample piston, in order to develop the proper technique for maintaining adequate search unit alignment.

The search along the first major web is completed with a "static scan" from a position on the recessed area of the rim, and as close as possible to the edge of the inner piston diameter -- position "S" in Figure 7. At his point, with some 20 inches of cast iron directly below the search unit, no "far signal" reference indication should be received.

The entire search procedure, as outlined above, is now repeated over each of the remaining three major webs of the piston. Any piston which displays indications of a discontinuity in any portion of a major web, must be considered as defective, and that piston should be scheduled for immediate removal from the engine.

Inasmuch as the strength of the ultrasonic signal received from a reflecting surface, whether it be a crack or the opposite side of the object, will vary considerably as a result of such factors as sound angulation, transducer characteristics, degree of "coupling," etc., it is <u>not</u> considered practical to establish a positive, quantitative, flaw indication reflection value. Nevertheless, in spite of all these variables, most cracks will be clearly discernible as such, and any evidence of <u>suspected</u> cracking should be the cause for continued investigation and likely rejection of that particular piston.

CONCLUSIONS

1. The detection of incipient structural failure in large, nodular cast iron diesel engine pistons, utilizing non-destructive, ultrasonic testing methods has proved feasible, and decidedly superior to any system previously employed, from the standpoints of time, money, and equipment required for conducting such tests.

2. Through the application of this recently developed procedure, pistons installed in Enterprise Model DSG diesel engines can be successfully inspected without the necessity of removal from the engine, with the only disassembly required being the removal of the engine cylinder head.

3. With a detailed knowledge of piston configuration available, this identical technique can likewise be successfully adapted to the testing of pistons of other makes and models.

GENERAL COMMENT

In any consideration of the use of such a system it must be recognized that ultrasonic flaw detection procedures depend more upon the skill and experience of the operator for their successful application than do most other widely used methods for inspection. The ultrasonic technician must make an immediate interpretation of his oscilloscope display, and normally has no record of the display for future reference. The dangers inherent, therefore, in the use of ultrasonic equipment by unskilled personnel cannot be stressed too highly. Thorough training in the use of the ultrasonic equipment at hand is absolutely essential for dependable, consistent results in the application of this procedure.

REFERENCES

1. Report No. M133B-01-68 by the San Francisco Bay Naval Shipyard entitled, "Instruction/Procedure for In-Field Ultrasonic Inspection of Piston Crowns in Enterprise Diesel Engines."

2. Report No. TRA-203 NAVY by Thermo Research Associates, Inc., entitled, "Cause of Piston Failures."

3. Report No. 269.196 by Anamet Laboratories, Inc., entitled, "Non-Destructive Inspection of a Piston from Engine 66029."

4. Report No. M135E-1659-68 by the San Francisco Bay Naval Shipyard, entitled, "Failure Analysis of Enterprise Piston for Enterprise Engine Model DSG."

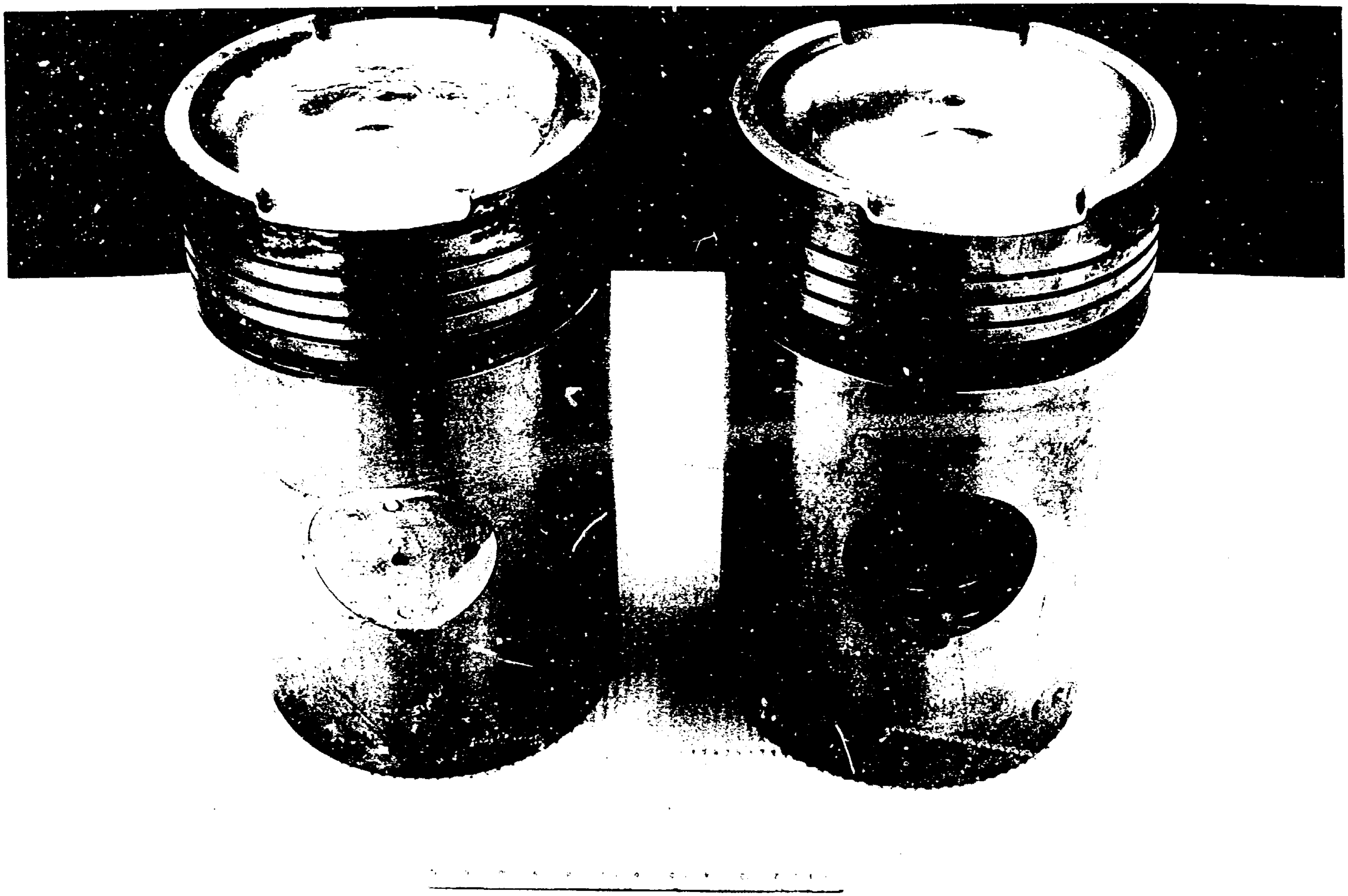
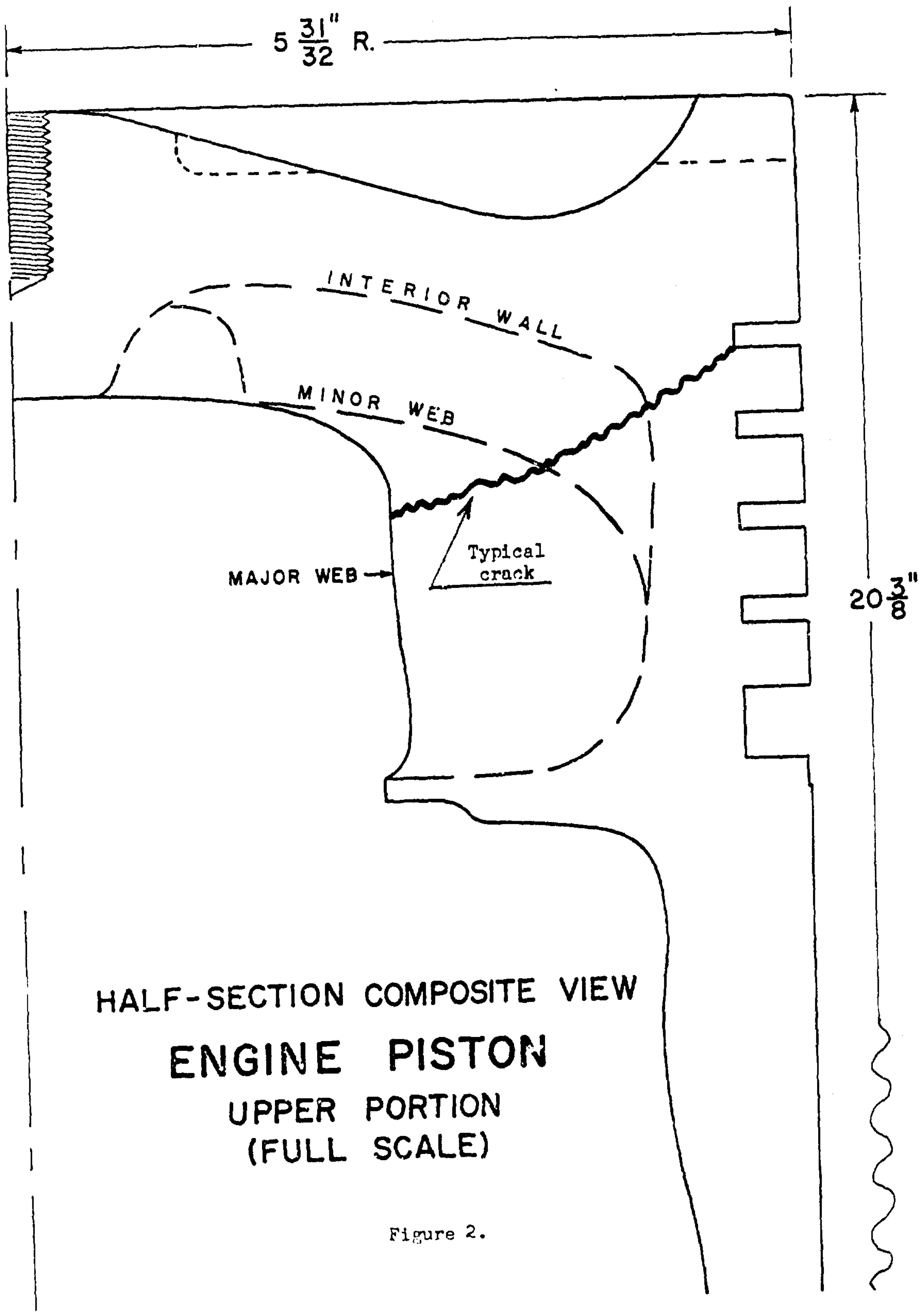


Figure 1. Enterprise Pistons. Part No. G-6924.



HALF-SECTION COMPOSITE VIEW

ENGINE PISTON

UPPER PORTION

(FULL SCALE)

Figure 2.

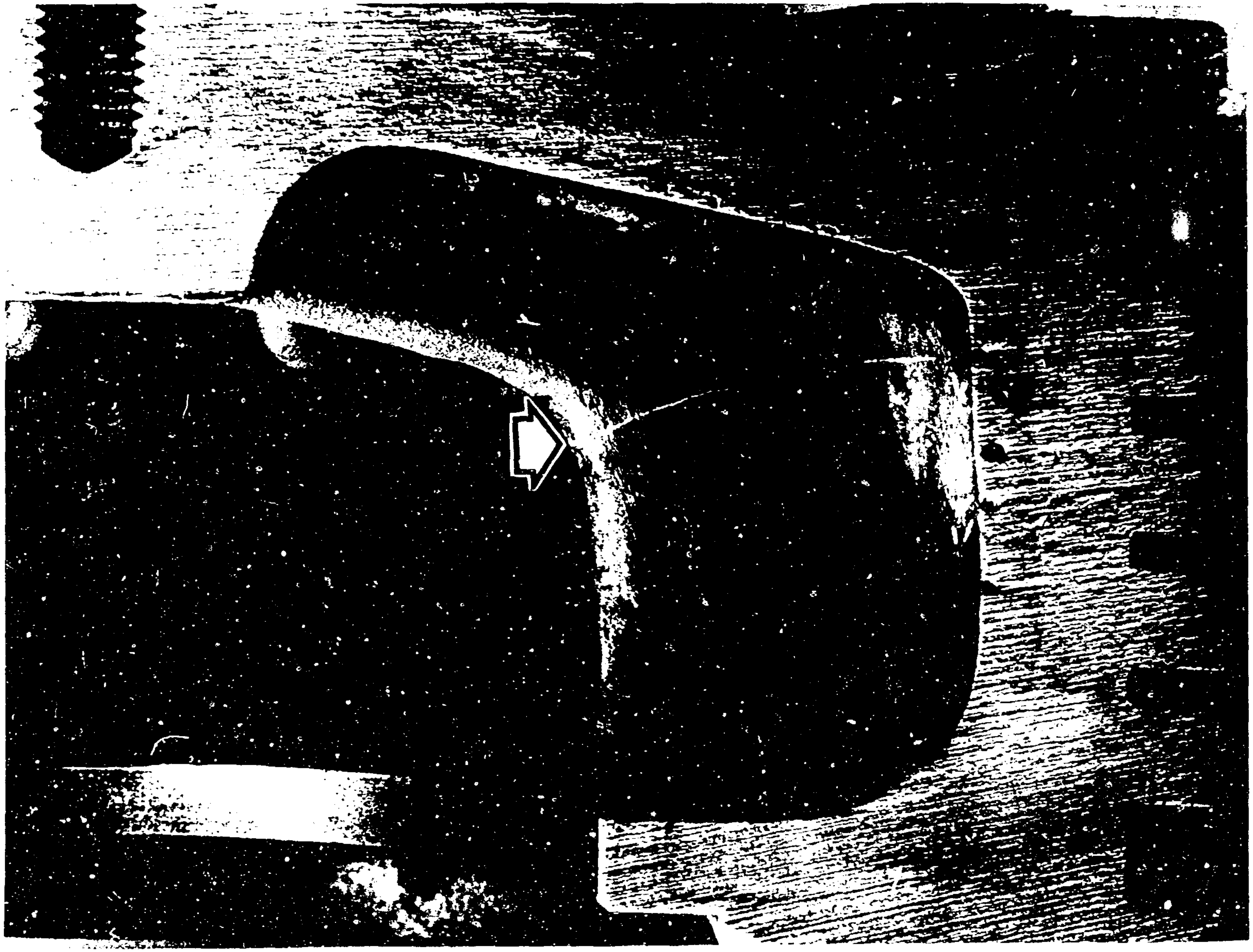


Figure 3. Fatigue crack in Enterprise piston. (1.5X)

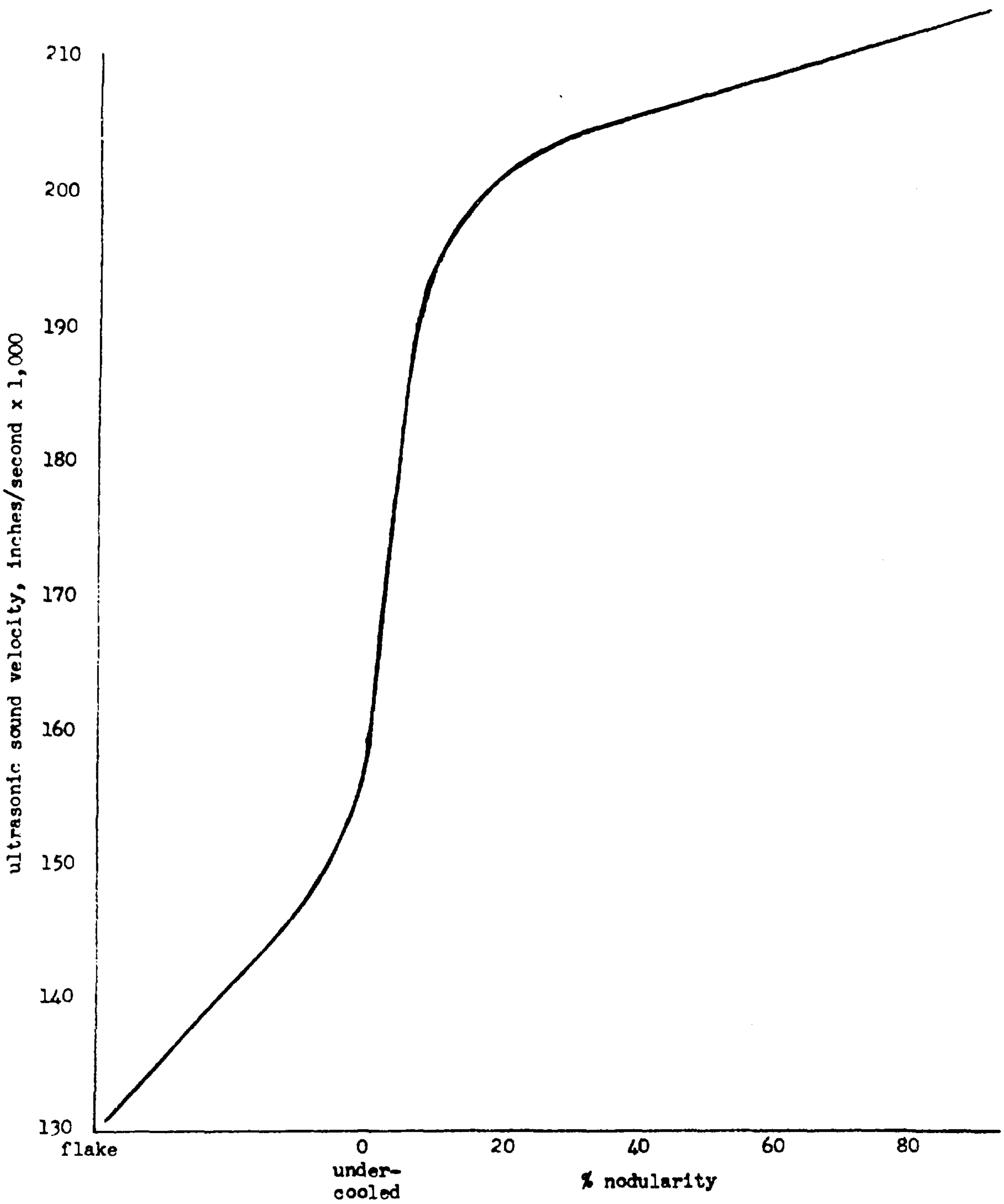


Figure 4. Sound velocity in typical cast irons.

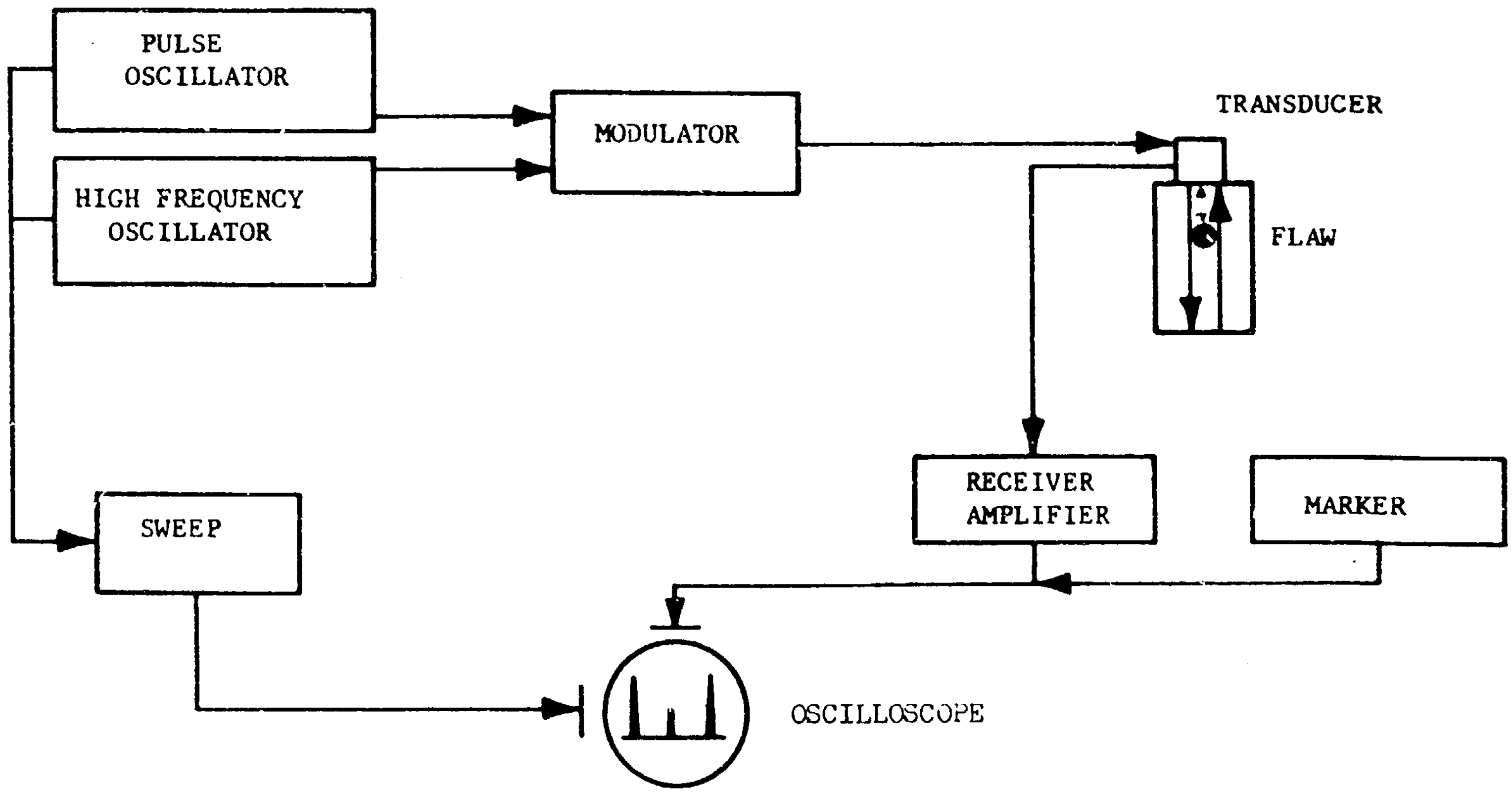


Figure 5. Ultrasonic pulse-echo **flaw detection system.**

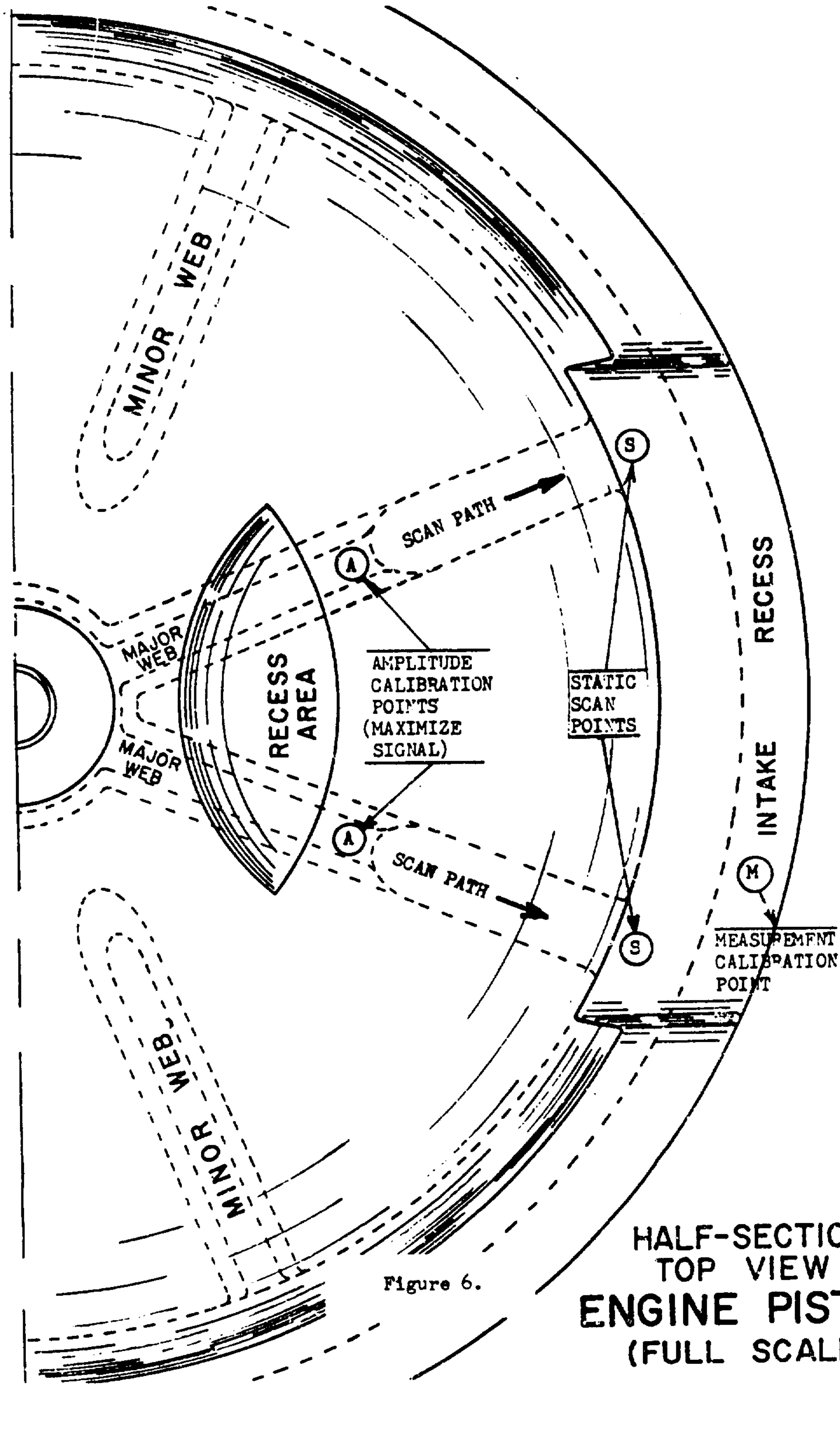


Figure 6.

HALF-SECTION
TOP VIEW
ENGINE PISTON
(FULL SCALE)

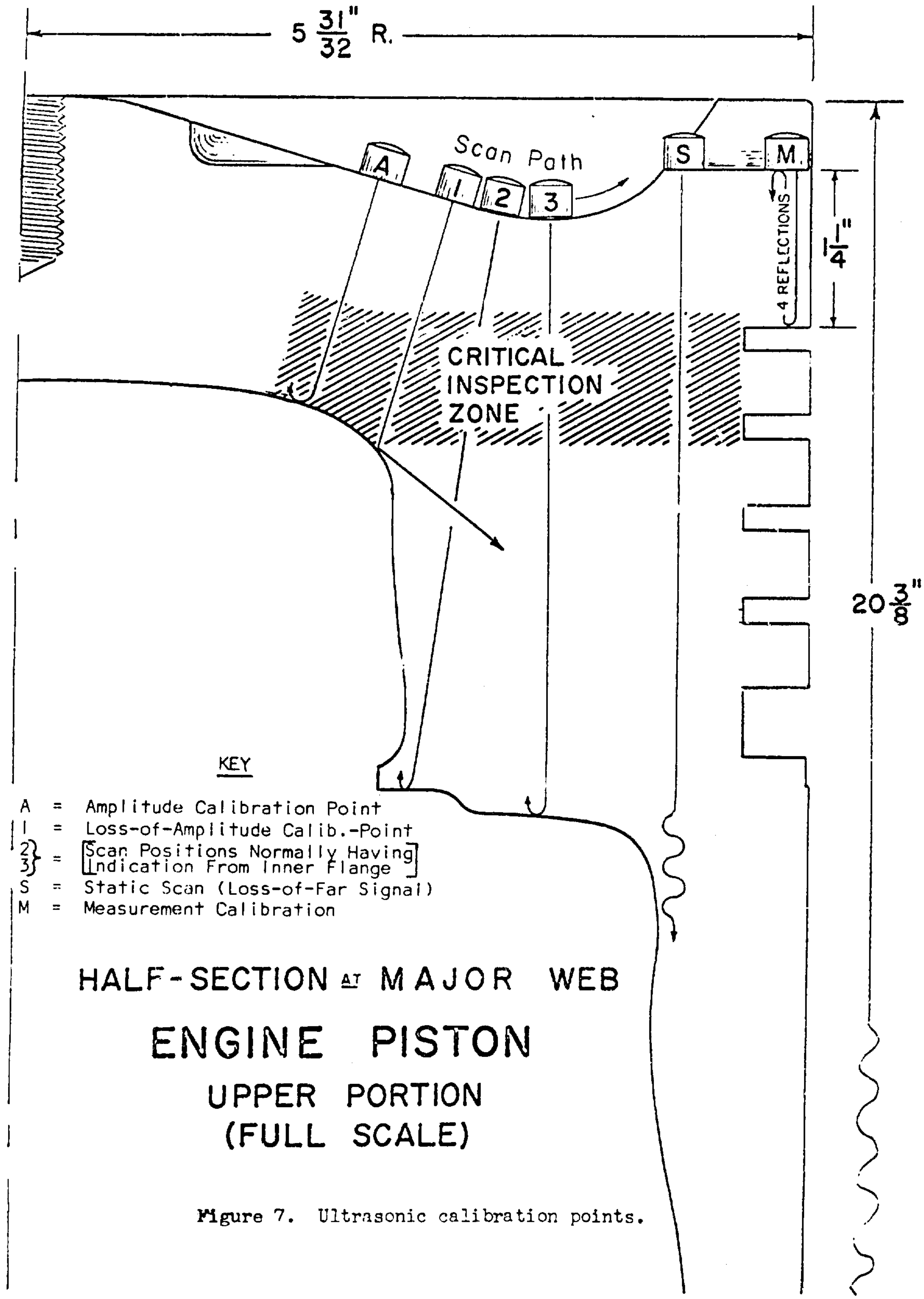


Figure 7. Ultrasonic calibration points.

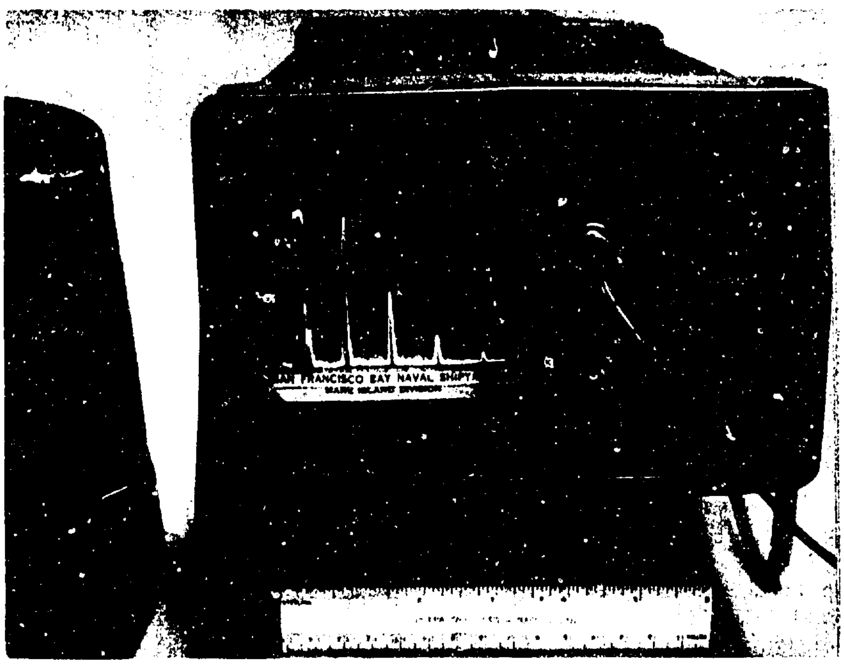


Figure 8. Depth measurement calibration.

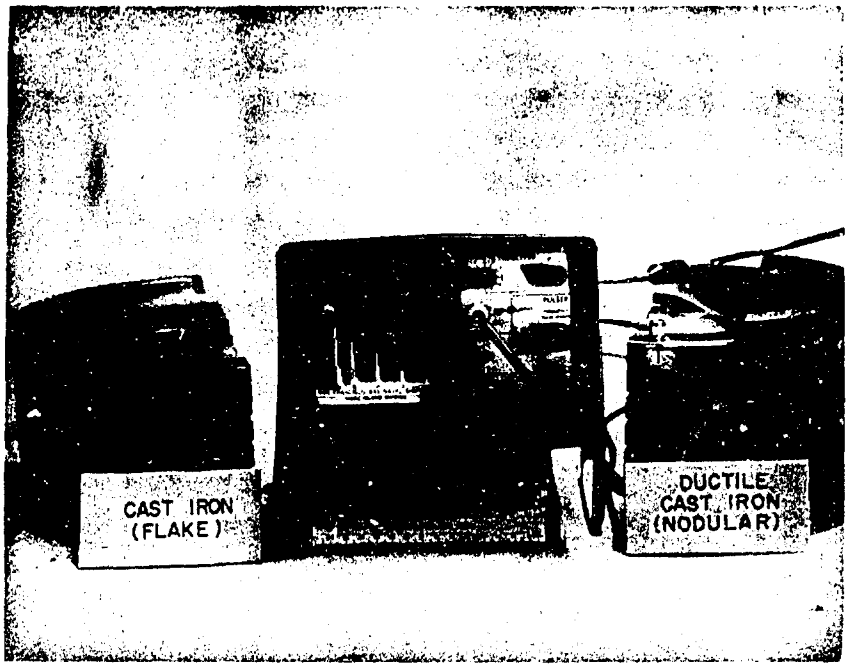


Figure 9-A. Satisfactory oscilloscope display - nodular cast iron.

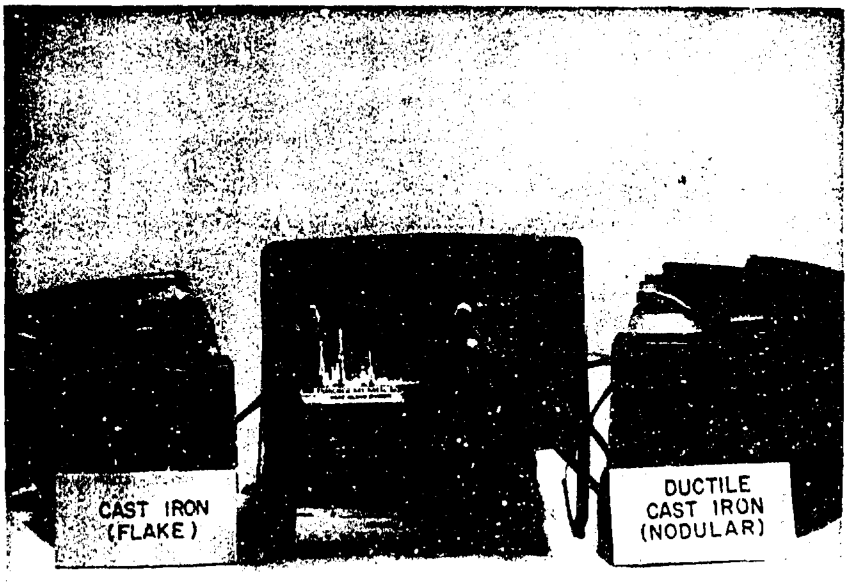


Figure 9-B. Unsatisfactory oscilloscope display - flake cast iron.

Figure 10. Oscilloscope display of cracked web.

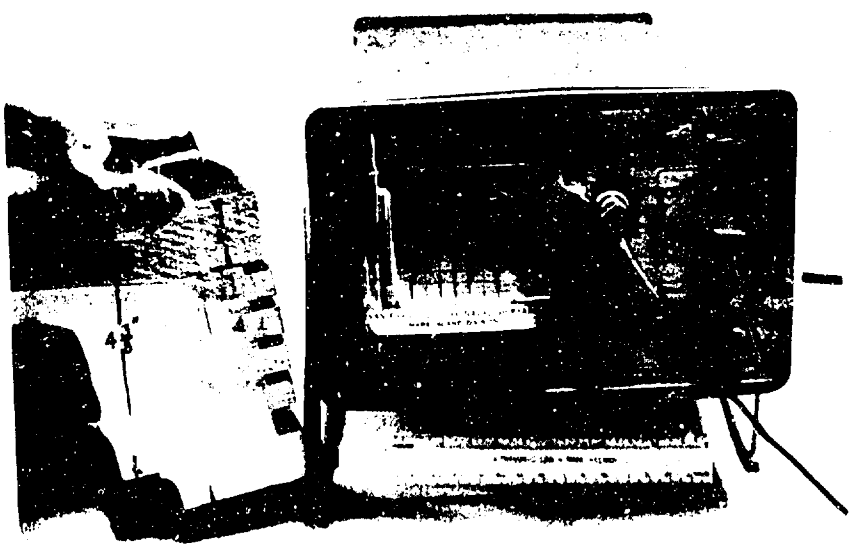


Figure 11. Acceptable major web at 4 3/8" thickness.

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The only major constraints in the application of this technique are the requirements that: (1) the piston material be homogeneous, (2) detailed information relating to piston configuration be available, and (3) the diagnosis be made by technical personnel experiences in ultrasonic interpretation.

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Prevention						
Failure						

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